Three Dimensional Vortex Shedding from Circular Cylinders

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LONG-TERM GOALS

Shear flow past slender bodies is a very common configuration in many real life situations. The flow-induced oscillations have profound effect on the stability of the structures. The long-term goal of the current research is to understand the three-dimensional behavior of the emerging unsteady flow field behind a slender circular structure when the upstream has a linear shear. Such an understanding will not only elaborate the frequency response of the unsteady forces on the cylinder but will also enhance the knowledge of the formation of spanwise vortical cells.

OBJECTIVES

To conduct detailed numerical simulations of the time-evolving laminar flow over a circular cylinder with spanwise non-uniform approach flow. The Reynolds number range is chosen such that at all spanwise locations the flow is nominally two-dimensional in the absence of shear. The objectives of these simulations are to understand the following:

- Mechanism responsible for cellular shedding;
- Distributions of pressure and velocities inside the spanwise cells;
- Topological aspects of the vortex dislocations;
- Effects of spanwise boundary conditions;
- Temporal behavior of the cellular shedding pattern.

In addition, time-averaged velocity fields are analyzed by averaging the instantaneous data.

APPROACH

Unsteady flow behind circular cylinders with shear in the approach flow has been so far studied mostly by experimental techniques. Such studies have shown the existence of the spanwise cellular structure.

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A few other studies have simulated the vortex shedding phenomena using oscillator models. These studies have reasonably captured the frequency response of the flow. However, the evolution of three-dimensional flow field and the resulting cellular vortex structures are not well understood. In the present study, an attempt is being made to explore, through direct numerical simulations, the dynamics of the flow and the spanwise cellular vortex shedding phenomenon.

In the present investigation, we have used a computer program based on the finite volume method with co-located variables and a curvilinear grid. For time integration, a two-stage, second-order accurate Adams-Bashforth scheme is used. The first stage of the integration consists of solving the momentum equations for an intermediate velocity field. This step is followed by the solution of a Poisson equation for pressure. To minimize the influence of numerical (artificial) diffusion effects, all the spatial derivatives have been discretized using a central difference scheme. The pressure equation is solved using the conjugate gradient method.

After the impulsive start, the flow is allowed to develop for several tens of dimensionless time units. Transient field data are then collected for several cycles of the vortical oscillations in the 3D wake. Through extensive post processing, transient data are analyzed to explain the evolution of the flow field in terms of instantaneous and time average vorticity, velocity, pressure and frequency spectra at several downstream points.

WORK COMPLETED

A number of 3D simulations have been completed. These computations confirm both qualitatively and quantitatively, the aspects of cellular shedding also reported by several previous investigators through experiments. In a parallel effort, another code for orthogonal r-θ-z co-ordinates has been developed. This code is also based on identical discretization and temporal integration schemes. However, this code treats diffusion implicitly in azimuthal and radial directions. The pressure Poisson equation is solved directly using a FFT based solver. This code has been validated for the case of uniform approach flow. This code has enabled us to go for a much finer scale computation with 256 x 256 x 128 (i.e., 8 million) nodes. Both codes have been parallelized using the Message Passing Interface (MPI).

Following is a list of simulations that are being performed:

Run #	Code / Grid	Domain Size	Reynolds # Range	Spanwise Boundary Condition	Status
1	BFC / 80x80x120	R = 15d; Z=24d	100 - 163	Free-slip	Completed
2	BFC / 80x80x120	R = 15d; Z=24d	100 - 163	End-plate; Free-slip	Completed
3	BFC / 80x80x240	R = 15d; Z=48d	68 - 194	Free-slip	Being analyzed
4	BFC / 80x80x240	R = 15d; Z=24d	100 - 163	Free-slip	Being analyzed
5	rθz / 256x256x128	R = 30d; Z=24d	100 - 163	Free-slip	Running

RESULTS

The present computations confirm for the first time many of the features reported previously by experiments for shear flow over a circular cylinder. A definite cellular pattern of vortex shedding along the span of the cylinder is observed. Up to five distinct cells for a cylinder of 24 diameters span have been observed. The lengths of the cells varied between 3 and 7 cylinder diameters. For the free-slip boundary condition with a cylinder of L=24d, the Strouhal numbers based on centerline free stream velocity ranged between 0.14 and 0.205 (Run 1; Figure 1), the smaller value being at the minimum velocity end. With the no-slip boundary condition, the corresponding limits were 0.135 and 0.183 (Run 2). The Strouhal numbers based on the local velocities varied linearly in each cell. Instantaneous base pressure plots show correspondence with cellwise shedding pattern, as reported by Maull and Young. However, the time averaged base pressure varies smoothly along the span (except for end effects) and masks the cellular pattern. Vortex dislocations are observed to form near the high velocity end, and to get convected to downstream axial locations. Even though there is a significant spanwise pressure gradient upstream of the cylinder, there is no significant spanwise velocity.

The results with a no-slip boundary condition (Run 2) at the ends are very similar to those with free-slip condition (Run 1), except for the end wall boundary layers and the corresponding vorticity that is generated. The cellular shedding is observed in both cases. The frequency spectra alone may not be the best indicator of the cellular shedding pattern. Detailed spanwise distributions of the velocity, vorticity and other quantities should be also studied along with the frequencies of vortex shedding.

The present calculations reveal that the flow continually develops in time, in a very complex manner. In order to study the temporal dynamics in more detail, it seems necessary to integrate the equations for much longer time.

The effect of spanwise domain size has been investigated by considering a cylinder of length 48 diameters (Run 3). The frequency of vortex shedding has been monitored by collecting cross flow velocity signals at downstream locations of x = 7.5D, y = 0. Figure 2 shows the frequency spectra of these cross flow velocity signals. The presence of nine constant frequency cells is evident from this figure. The variation of base pressure over the span of the cylinder at various time instances shows that the cell boundaries coincide with valleys in the base pressure curve and they are continuously moving in time. The time averaged base pressure varies smoothly along the span. Vorticity iso surfaces (Figure 3) show similar cellular pattern with alternate positive and negative distributions. Additionally the oblique shedding is clearly observed. The cell boundaries are regions where positive and negative vortices meet. The obliqueness in the vorticity contours indicates a relative increase (across the span of a cell) of the convective velocity of these vortices. One can also observe the appearances of vortex dislocations at the high velocity end, similar to Runs 1 and 2.

The effects of grid resolution in the spanwise direction is examined in Run 4, by considering a grid spacing of 0.1D (earlier simulations were done with a grid spacing of 0.2D). Frequency response is observed to be quite the same as in Run 1. The results obtained from this simulation justify applicability of an economic spanwise grid spacing of 0.2D. Another simulation is currently underway (Run 5) to investigate the effects of downstream domain size. The extent of the downstream domain in this simulation is 30 cylinder diameters (all the simulations mentioned before considered a downstream domain size of 15 cylinder diameters).

IMPACT/APPLICATIONS

Flow over bluff bodies has been of scientific interest for several decades. Almost all of these studies were limited to uniform approach flow. However, in real life, a large number of situations exist that involve non-uniform approach flow. Linearly sheared approach flow closely approximates some real life situations. Studies available in open literature for the case of shear flow are mainly experimental with limited details such as frequency response and base pressure distributions. Observations made in these experimental studies were somewhat scattered and only the generic features of cellular shedding were identified and a temporal evolution pattern was conjectured. The present effort is the first detailed numerical study of such a complex flow, revealing the wake dynamics and the spatio-temporal evolution of the cellular-shedding phenomenon. This has been possible with the availability of powerful supercomputing platforms.

RELATED PROJECTS

We are using the same computer program for LES of solid fuel rocket motor core flow fields.

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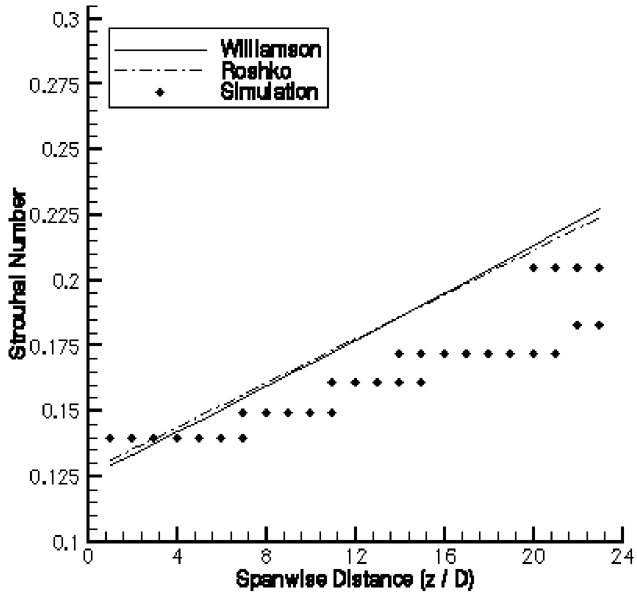

Figure 1. Spanwise variation of Strouhal number for Run 1

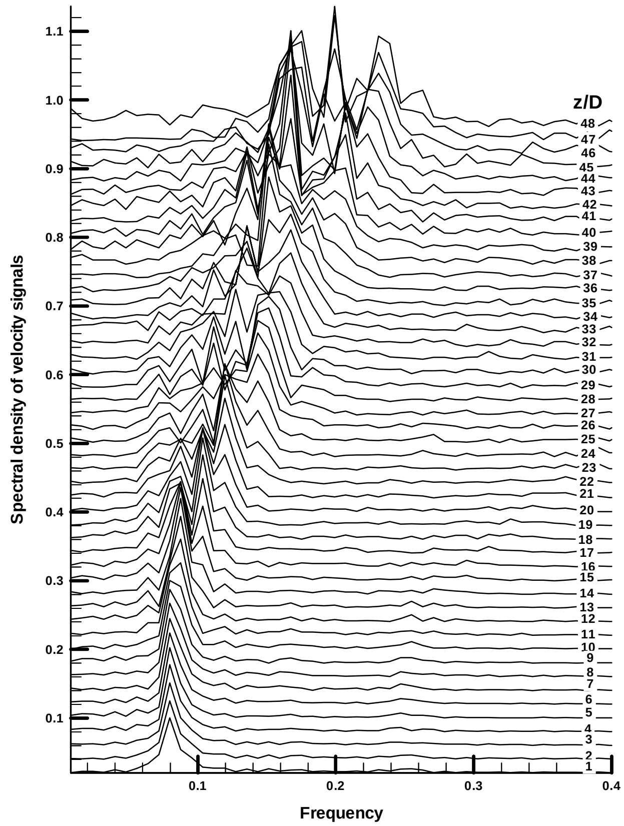

Figure 2. Frequency spectra of crossflow velocity for run 3.

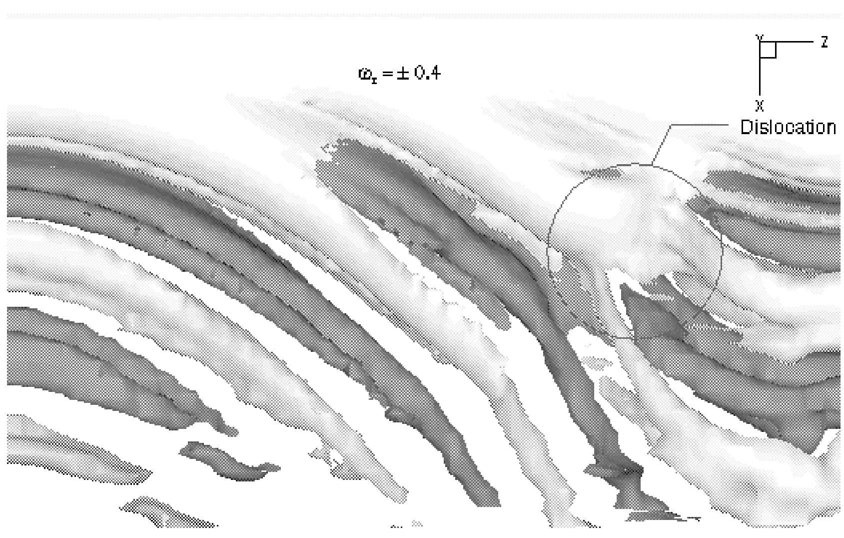

Figure 3. Iso-surfaces of spanwise vorticity ($\omega_z = \pm 0.4$)